

New Dimensions of Quarks and Gluons: Strings Return to Their Roots

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Heavy Ions, String Theory, and Cold Atoms”
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The Goal

We need to understand this new type of behaviour

These phases are interesting in their own right...

These are new phases of matter!

Hot, dense soup of Quarks and Gluons

Cold droplet of Lithium atoms

...but may have a lot to tell us about Physics in ultra-extreme conditions in Nature

Exciting and Novel!

How often do we create new phases of matter in the lab?!

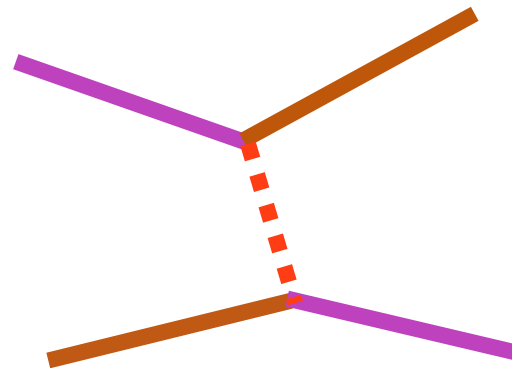
early universe...

cores of compact stars...

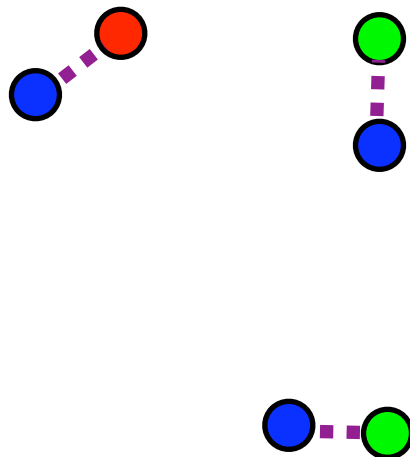
What Happened?!

Usual (QCD) picture:

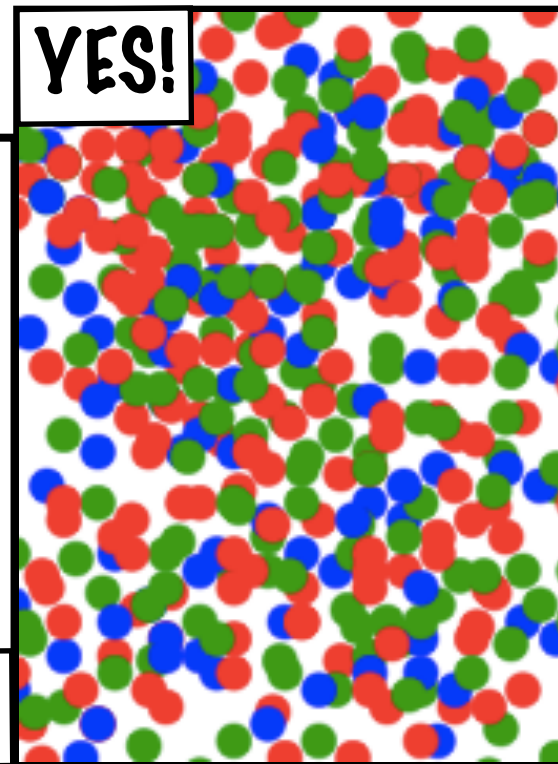
quarks interact by
gluon exchange...



But we can no longer
treat the quarks and
gluons as interacting
a few at a time...



YES!



NO...

"Collective Behaviour" emerges!

Behaviour of individuals vs.
Behaviour of a crowd.

Same sort of physics
emerging in certain
cold atom systems...

Understanding the Physics

How to
understand
all this?



Need robust models
of these properties
for this new form
of matter.

Is a description in
terms of molecules
best for getting to
grips with wetness
of water?



Big Question...

Is a model of
quarks and gluons
the best starting
point?

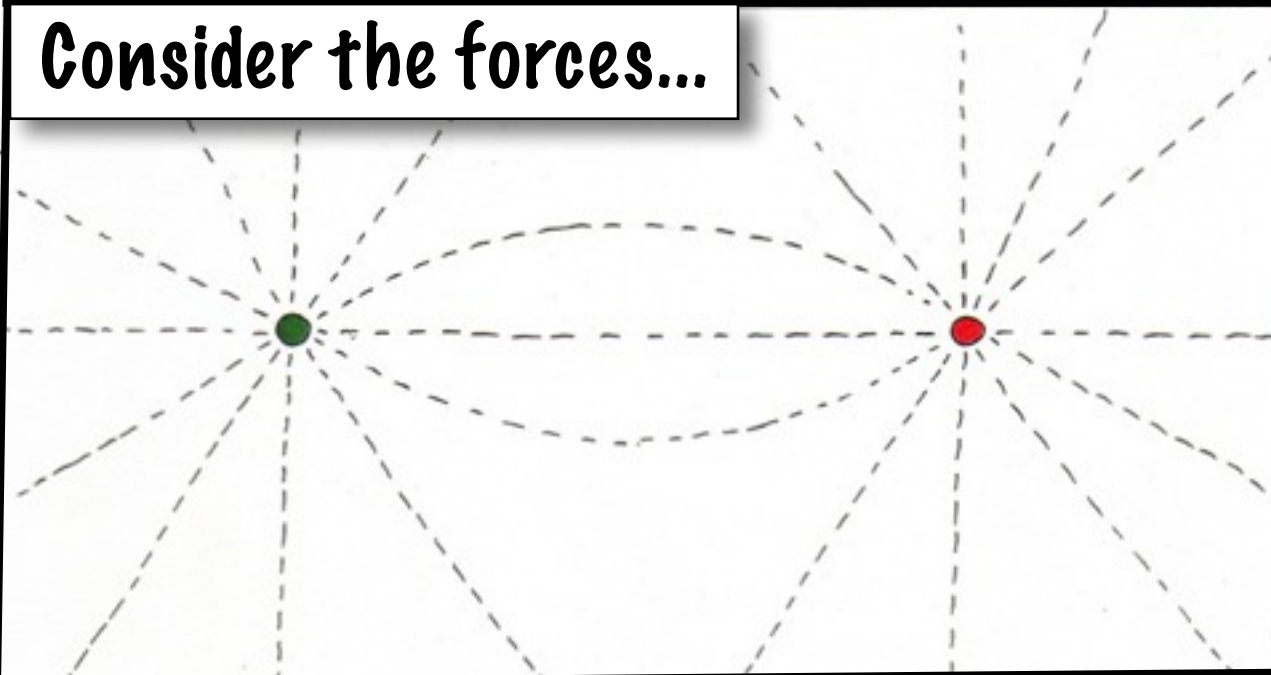
Is a model of
individual atoms
the best starting
point?

Are these the most natural
variables to describe the physics?

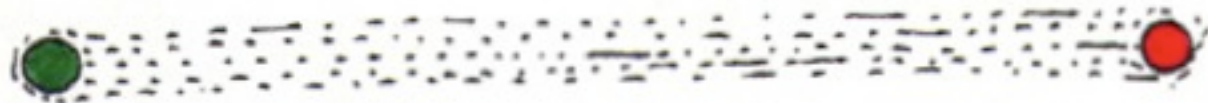
Perhaps the
answer is no...

Another Possibility

Consider the forces...



Can pull apart objects that interact electromagnetically until they are essentially free...



Is this all a clue?

Perhaps the right variables come from **strings!!**

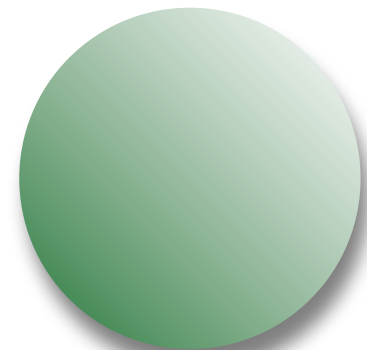
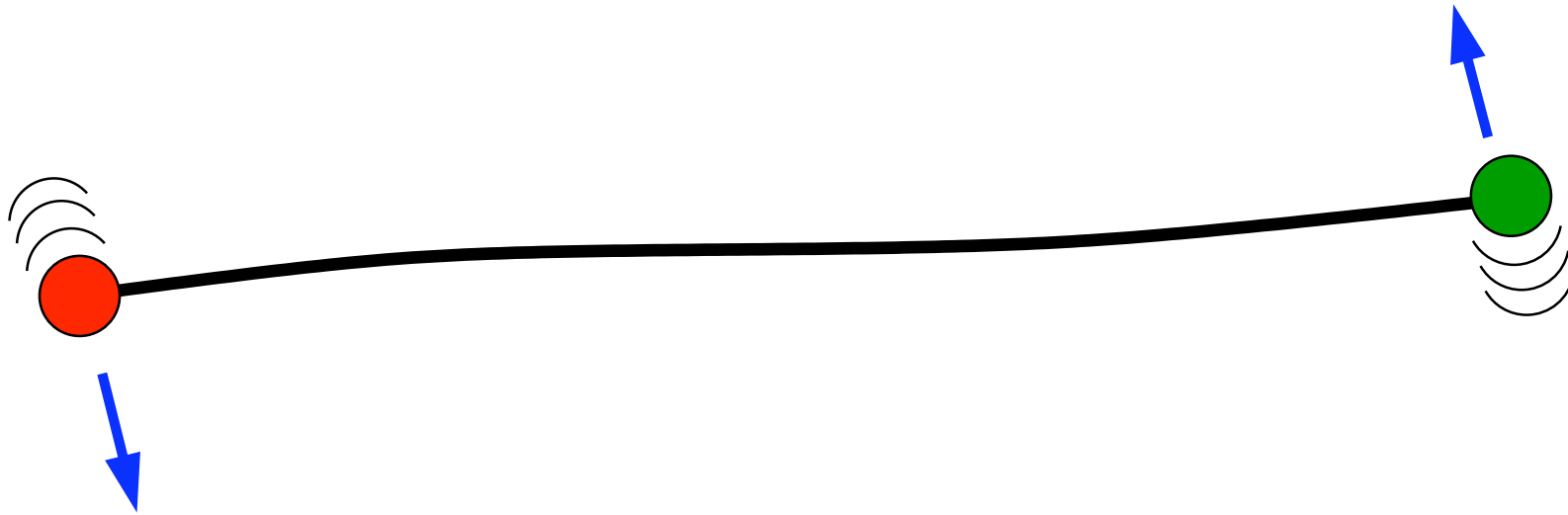
But not for quarks interacting with the strong nuclear force...

Goes back to the old ideas...

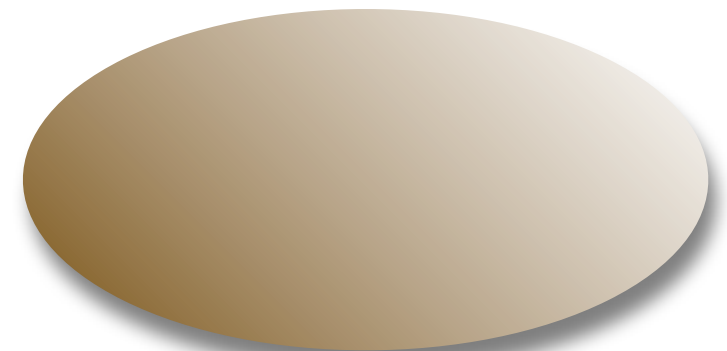
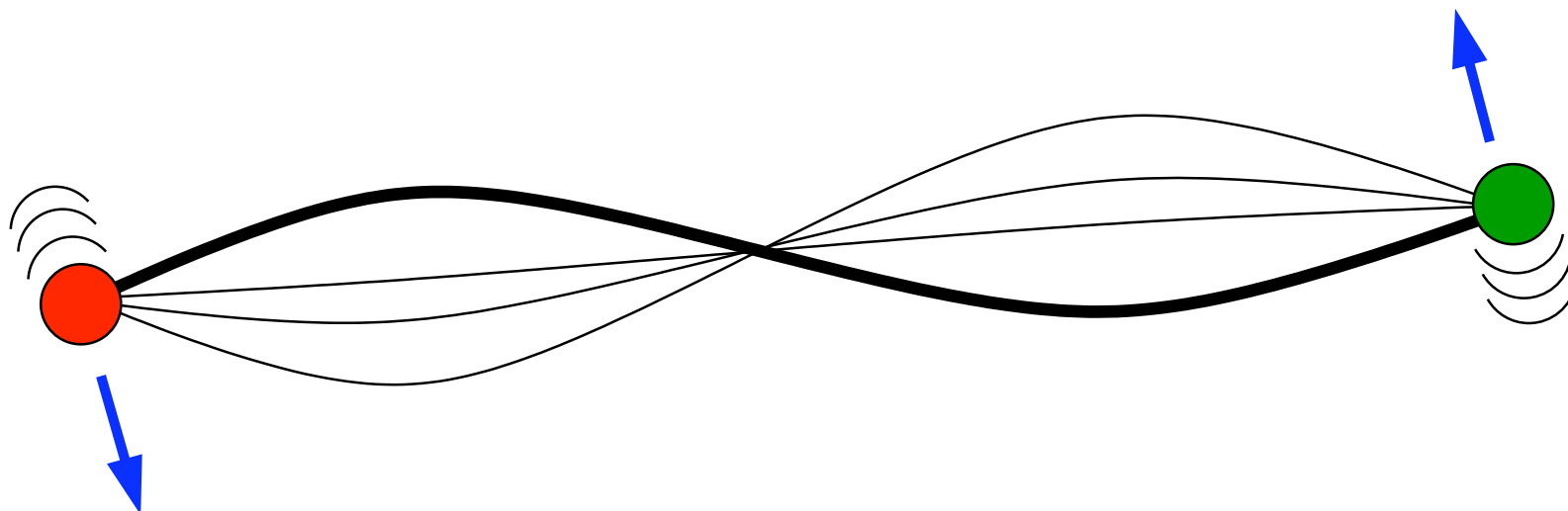
History I: The Old String Idea

The old ideas from the 60s and early 70s...

...different nuclear particles correspond to different vibrations and spinings of the string...



meson...



some other meson...

History 2: Strings Fail!

The physics of strings is very intricate. In order to work, the theory presents a list of demands:

There must be open strings and their vibrations...
There must be closed strings and their vibrations...
There must be more than three spatial dimensions...

There must be open strings and their vibrations...



There must be closed strings and their vibrations...



There must be more than three spatial dimensions...

Ok. That's where we came in. Works pretty well.

They describe a strange non-nuclear particle

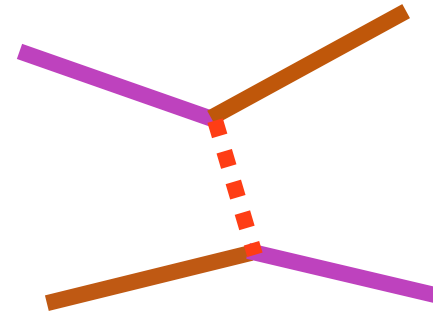
Ok.. that's the last straw...!

So clearly this is just wrong... right?

History 3: Quarks and Gluons Rule

These bugs - together with the QCD approach - killed the string attempt, in the 70s.

Quantum Chromodynamics (QCD)



Powerful for studying many aspects of quark-gluon physics

Crucial in high energy particle accelerators...



But these techniques fall short of what we need now...

History 4: Strings for Everything

Having failed to explain **something**, strings were resurrected in the late 70s and then the 80s in order to try to explain **"Everything"**

Everything?

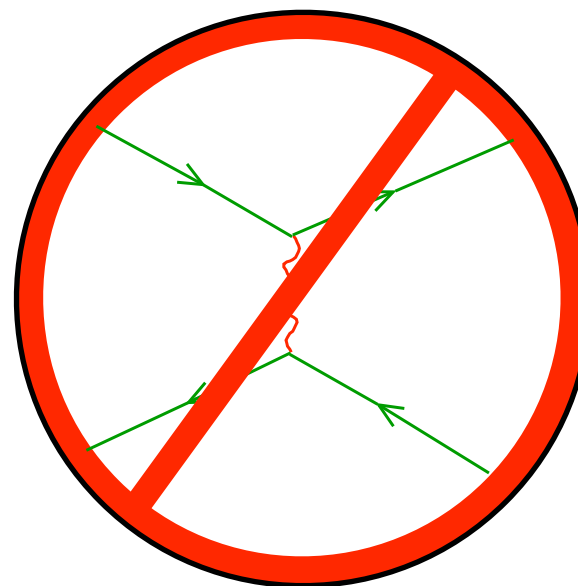
- Combine Gravity and Quantum Physics
- Unify gravity with the other forces
- Place all matter and interaction into one framework.

Ambitious and on-going...

Those vibrations look like "gravitons"!

Key idea comes from that funny closed string behaviour...

Perhaps it is **Quantum Gravity** that strings are good for!



NO...



YES!

Run with the idea...

Classical Black Holes

They arise as very simple solutions to Einstein's General Relativity

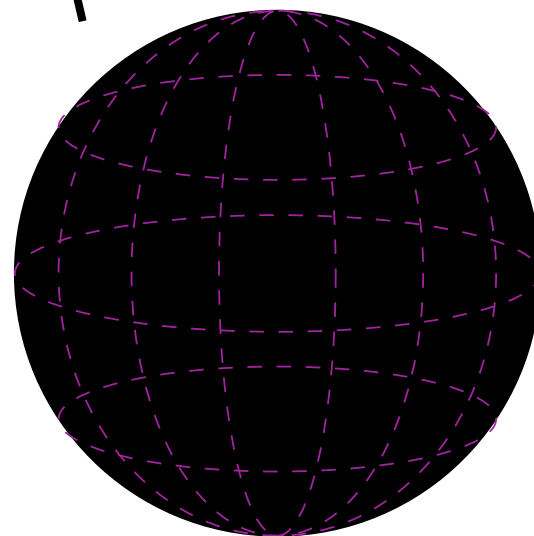
Simplest objects in the universe.

Whatever forms or falls into the hole, its details get lost: the black hole just gets bigger.

- Form from lots of mass-energy in small enough region
- "Nothing can escape, not even light" ("Black")
- Point of no return - Horizon

Horizon
"universalizes"
the physics.

Entropy
 $S=0$

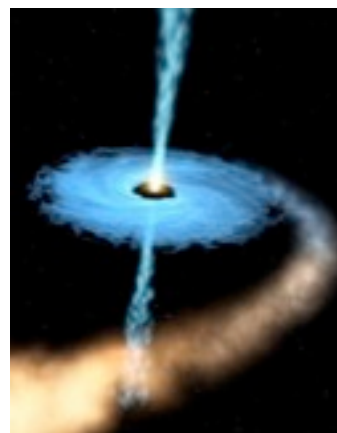


And they are really out there!

What of quantum physics?

For small enough black holes, quantum effects are important.

What are they?



Quantum Black Holes

Combine Einstein's General Relativity with quantum mechanics

$S \neq 0$ means they have an internal structure...!

Entropy

$$S = \frac{A}{4G}$$

String theory supplied a quantum gravity description of the physics of the internal structure.

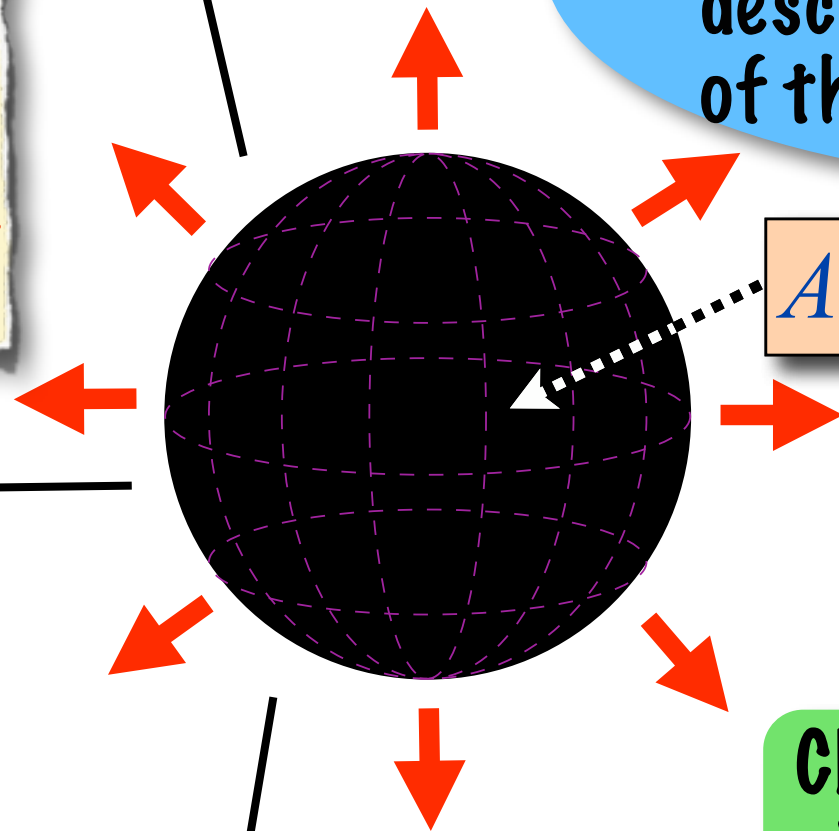
- Black holes radiate, acting like a body with temp. T
- Its mass can radiate away.
- Acts like thermodynamic object of entropy S .

$A = \text{area}$

We haven't yet found evidence of small black holes in our universe...

Clue: Entropy (information about interior) cares about area, not volume!

So what?



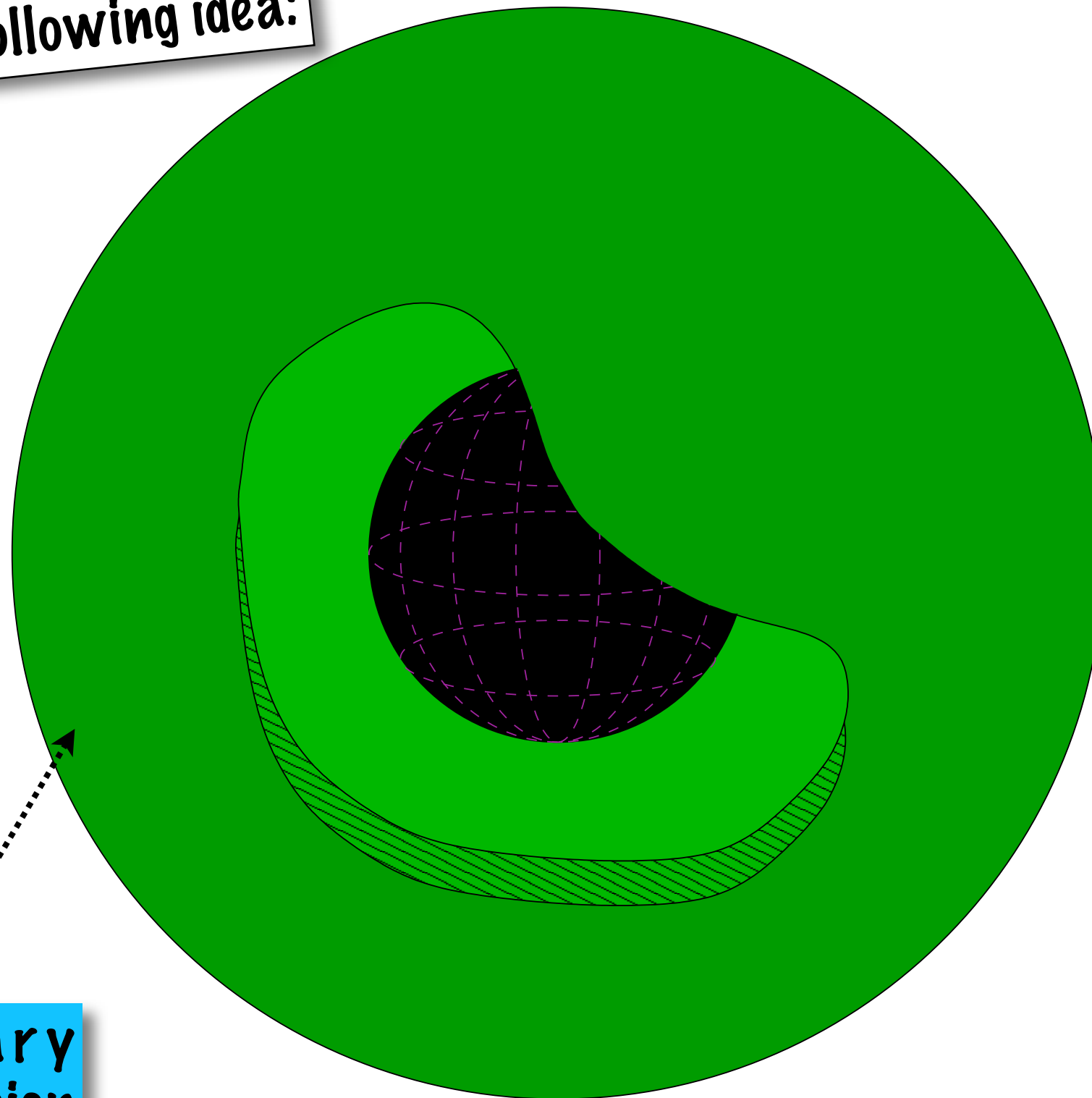
Holographic Principle

Studies led to following idea:

physics of black hole can be captured by staying at the walls of the box...

Quantum gravity systems have a description in terms of a non-gravitational system in fewer dimensions.

Build a box around the hole...

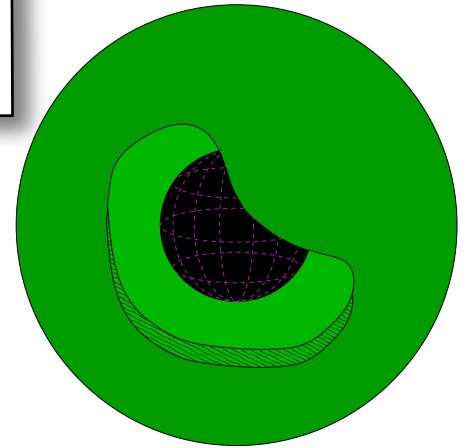


wall/boundary has one dimension fewer.

A Duality: Strings Return!

For black holes in certain
4+1 dim spacetimes:

the “holographic” description
resembles the type of physics
being seen in the experiments!



Black hole in higher
dimensional space,
so **not in our world!**

The bottom line...

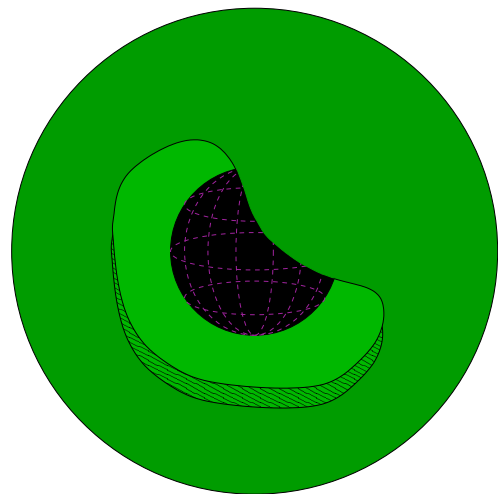
“Duality”: Same physics in very different systems

Have a dictionary to translate between
the **four** (space) dimensional quantum
gravity quantities and a **three** (space)
dimensional system!

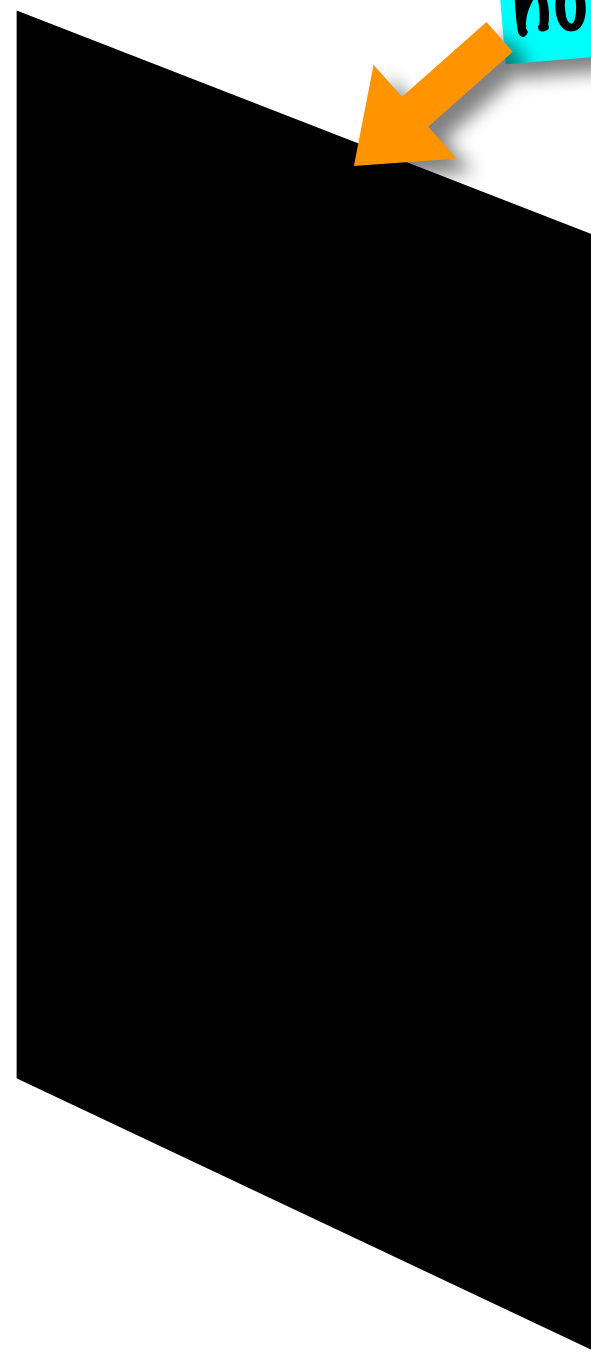
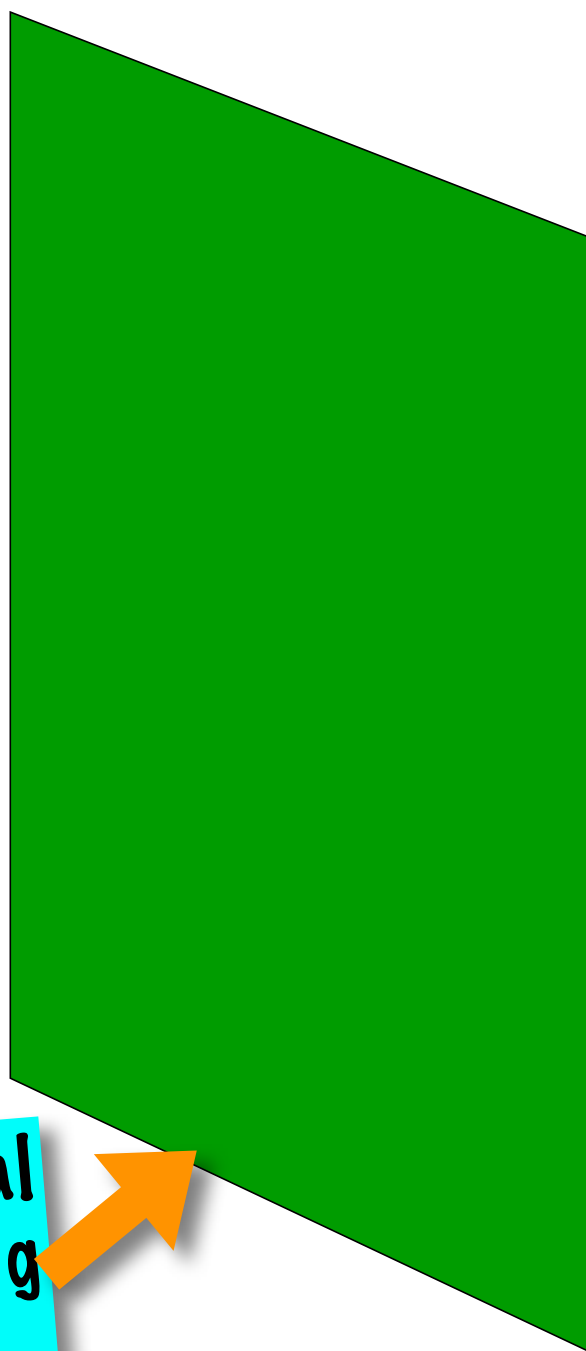
Turn this around to exploit it...

Easy to compute properties
of the gravity system
(black holes) determine
hard to compute properties
of the dual system of
interest.

Let's see how
it works...



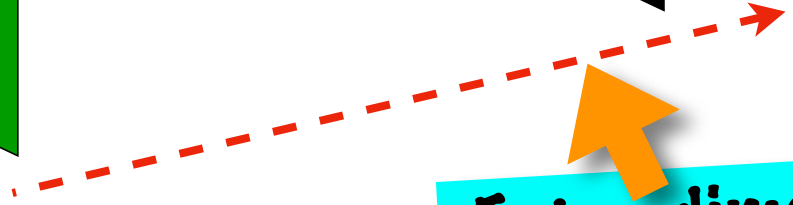
Typically work with
a close-up of this,
which opens it up...



Black hole
horizon

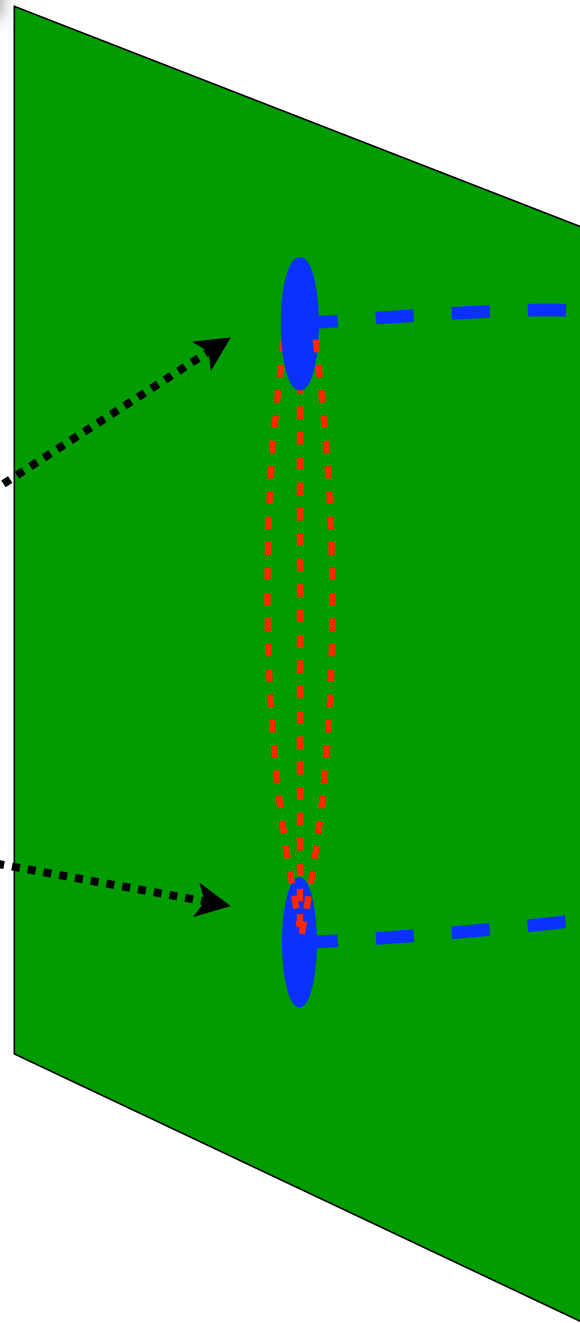
Three (space) dimensional
system we're studying
(plasma, or cold atom gas).

Extra dimension



The old ideas get to work after all. The bugs became features...!

quarks are ends of strings, living in the three space dimensions...



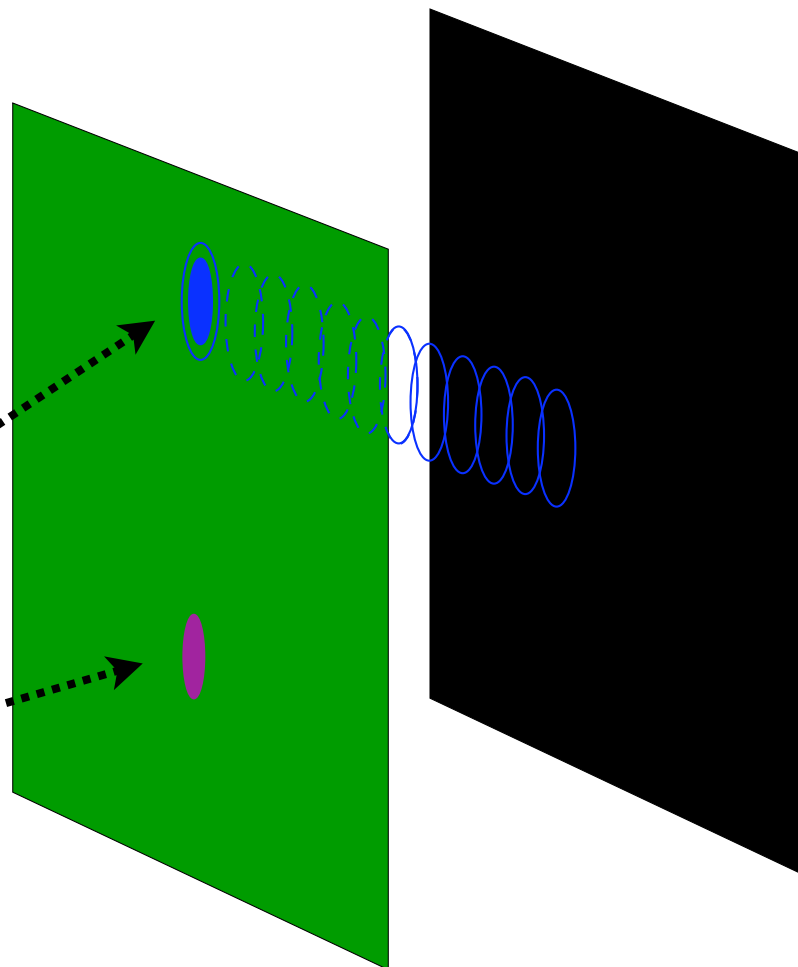
But the string that connects them reaches into extra dimensions!

closed strings move in the extra dimensions!

Key: Previous attempt was not using stringy ideas to address the right physical regime!

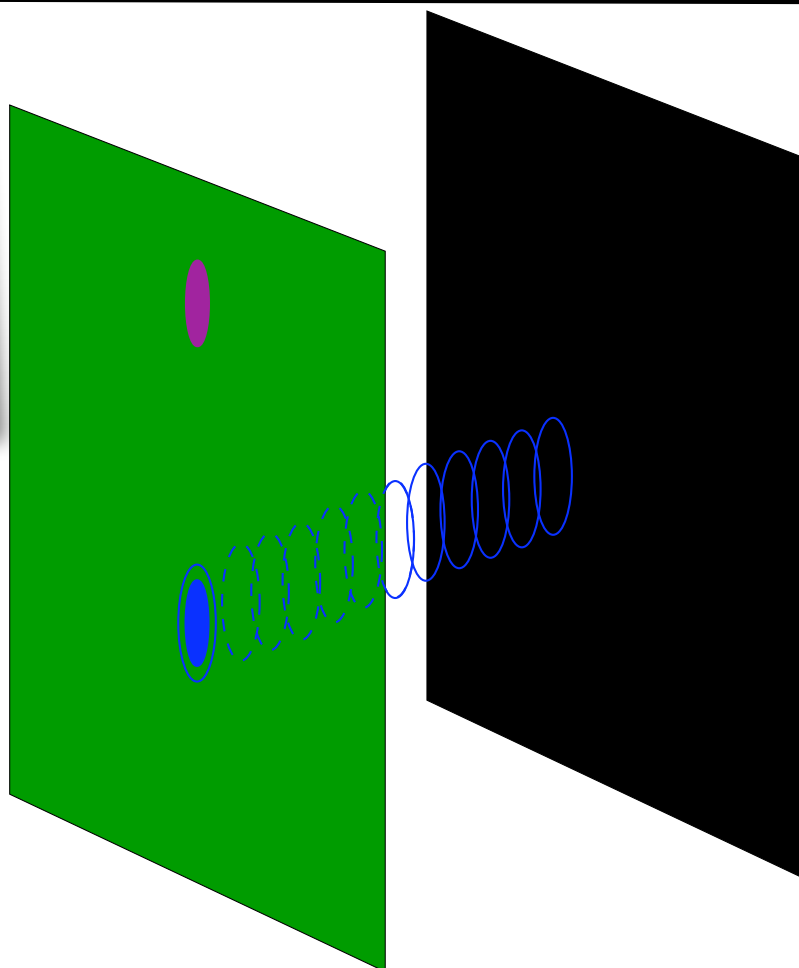
Computation of
the Viscosity...

See how two separated
points in the plasma
connect to each other...



The disturbance
travels as closed
strings (gravitons)
in the higher
dimensions...

...and scatters
off the black
hole before
returning!



Bigger black hole absorbs more,
reduces disturbance, increasing
viscosity.

viscosity

$$\eta = \frac{A}{16\pi G}$$

entropy

$$S = \frac{A}{4G}$$



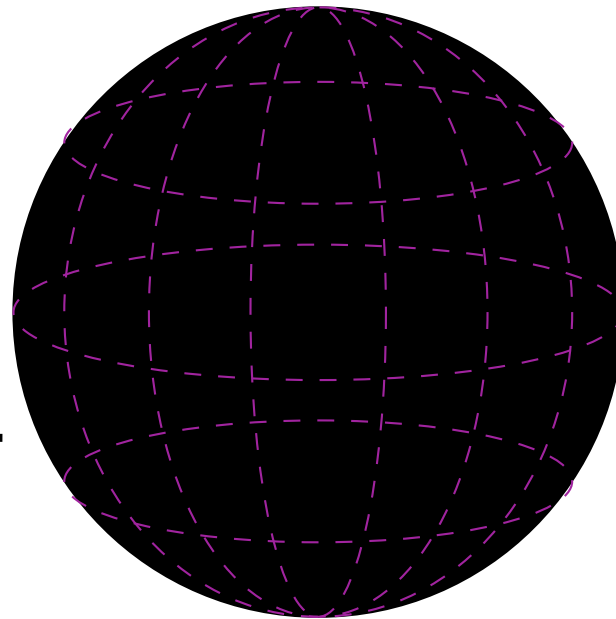
$$\frac{\eta}{S} = \frac{1}{4\pi}$$

Just what's
been seen!

Hopes and Expectations

The models so far are simple, so it is remarkable what they can already do...

Strings, gravity, black holes, etc, seem to supply the right variables for this physics.



Why does it work so well?

What are prospects for more success?

What are the "universal" features of our new variables that simplify the physics...?

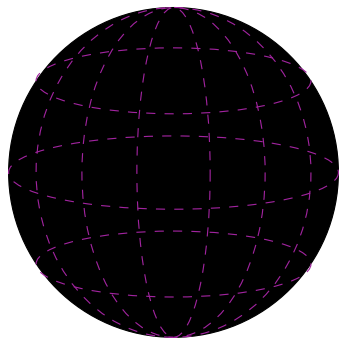
Black holes with their simple horizons...

Hopes and Expectations

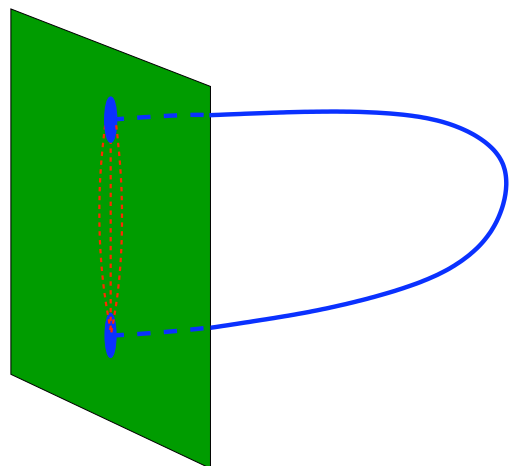
This is also a powerful test of the tools that come from string theory...



Perhaps more experiments may shape the theory in ways we have not thought of yet...



May feed back into other applications of string theory (unification, cosmology, etc...)



The work continues.
It is very exciting...!